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Hot water tanks : How to select the optimal modelling approach?

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Abstract

There is a rising interest for optimal use of thermal energy storages (TES) in buildings to improve energy efficiency and for load shifting in demand side management. In this context, a state of the art of the different methods for simulating sensible TES is proposed. Mathematical equations which describe the processes occurring in a sensible TES are difficult to solve with a simple formulation. That is the reason why a large number of storage models have been developed in the last decades. Few studies compare the different modeling approaches and their respective advantages and limitations. A review of the literature is thus performed and it focuses on eight different modeling approaches. The comparison is performed in terms of computational time, accuracy and application. A tree of selection is proposed to select the optimal TES modeling method for a given application.

Keywords - *thermal energy storage, modeling, sensible storage, domestic application, stratified tank, review*

1. Introduction

The building sector accounts for one-third of the global final energy demand [1]. Thermal Energy Storages (TES) play a significant role to reduce the impact of the building sector on the environment. TES have numerous advantages [2]:

- Enable a fundamental balance in energy supply-demand dynamics, which often do not occur at the same periods, especially in future energy systems based on renewable energy. ;

- Decrease the number of starts and stops of the heating system, thus decrease their energy losses;
- Increase deliverable capacity (heating element generation plus storage capacity);
- Shift energy purchases to lower cost periods;
- Increase system reliability.

The most important factor influencing the efficiency of hot water tanks (most widespread technology) is the vertical thermal stratification. An efficient storage conserves hot water in the upper part to limit unnecessary heating and cold water at the lower part to optimize heating system performance in the case of heat pump or solar collector. A short thermocline (layer in which temperature changes more rapidly with depth than it does in the layers above or below) allows reducing the mixing and avoids the destruction of exergy [3].

To improve the efficiency of these systems an accurate model of the hot water tank and its stratification is necessary. On the one hand, a poor tank model underestimates/overestimates the efficiency of the TES and therefore leads to over/under-sizing of the system. Sizing is crucial for different reasons. Over-sizing leads to higher investments and potential wasting of electricity if more energy is stored than is required (high losses). Under-sizing leads to more start and stops, reduced possibility of shifting production and demand, poor levels of indoor comfort and lower solar fraction if integrated in a solar system. While, on the other hand, optimal control strategy through accurate modeling allows significant higher annual performance of the system.

In practice, modeling the behavior of hot water tanks is not trivial. A wide range of typologies (series, parallel, hybrid connections with loads and heating systems), materials (fluid, tank and insulation) and geometries (tank port type, orientation and location, internal or external heat exchangers, electrical heaters) exist. Following an introduction (section 1), this paper briefly describes the different phenomena that take place in a sensible water storage (section 2). Thereafter, a classification of storage models and a brief description is proposed (section 3). Finally, a comparison and a tree of selection is proposed (section 4).

2. Description of the physical processes

Different physical processes can occur in a hot water tanks:

- Heat transfer by conduction in the water due to temperature gradient;
- Ambient losses due to the temperature gradient between the storage medium and the ambience;
- Convective currents induced by parietal heat transfer [4]. The tank wall cools a thin vertical layer of water adjacent to the wall. This

water layer becomes denser than its surroundings and slips towards the bottom of the tank (Fig. 1a);

- Buoyancy induced flow by temperature inversion due to loading conditions (Fig. 1b). This takes place when cold (i.e. hot) fluid enters a warm (i.e. cold) layer. This could, for example, happens when using a solar heating system in the late afternoon;
- Mixing with jets (during direct charging or discharging of the tank, the fluid entering the tank presents a certain level kinetic energy that will lead to a mixing of the temperature inside the tank);
- Quilting, which is a heat loss due to recirculation of water in the tank from hydraulic connections;
- Heat transfer through exchanger or resistor;
- Obstacles to decrease momentum driven jets (Fig. 1c).

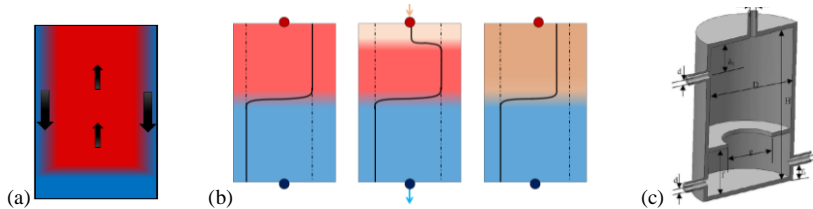


Figure 1: (a) Convective currents induced by parietal conduction. (b) Buoyancy induced flow by temperature inversion due to loading conditions [5]. (c) Obstacles to decrease momentum driven jets [6]

3. Description of different modeling approaches

Mathematical equations that describe the processes occurring in the storage are difficult to solve without considerable simplifying equations. That is the reason why a large number of storage models have been developed in the last decades. Some applications require fast computational time with low accuracy while other need very accurate modeling of all the phenomena occurring in the tank. The following classification is proposed to group types of model (Fig. 2): Analytical (AN), Fully Mixed (FM), Blackbox (BB), two zone Moving Boundary (MB), Plug-Flow (PF), Multi-Node (MN), Zonal (ZN) and Computational Fluid Dynamics models (CFD).

a. AN - Analytical

Some authors ([7,8] among others) developed an exact analytical solution of storage modelling.

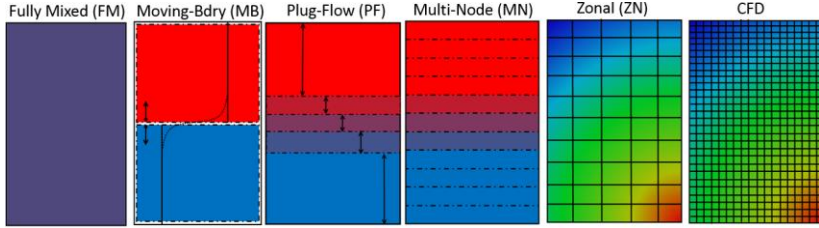


Figure 2: Different modeling approaches for a sensible thermal energy storage.

A Laplace transformation technique is used to predict the thermocline during charging. These models are based on several hypothesis. First, the tank is modelled as a one-dimensional semi-infinite body to make the problem mathematically tractable. Also, no mixing or ambient heat losses are considered. Finally, the thermo-physical properties, the inlet temperature and the mass flow rate are kept constant. This model has a narrow range of application but demonstrates to be very fast. However, this model is interesting to evaluate the upper bound achievable in terms of stratification. Also, it helps to find general correlations, [8] showed that the thermocline thickness in the case of no fluid mixing at the inlet in a charging process is proportional to the square of root time and reversely proportional to the flow rate.

b. FM - Fully Mixed (or one layer or thermal capacity)

The fully mixed model is the simplest and one of the fastest since the temperature is considered homogenous in the whole tank. The energy balance (Eq. 1) takes into account the inertia of the fluid, the heat input (\dot{H}_{in}) and output (\dot{H}_{out}) and eventually ambient losses (\dot{Q}_{amb}). m is the mass of fluid, c the specific heat capacity and T , the homogenous temperature.

$$mc \frac{dT}{dt} = \dot{H}_{in} - \dot{H}_{out} - \dot{Q}_{amb} \quad (1)$$

Of course, no stratification is possible leading to a significant error on the estimation of ambient heat losses. Poor performance is therefore achieved for the heating system in the case of a heat pump or a solar collector. This model could be seen as a Multi-Node (MN) model with one node. But, practically, with only one node, all the physical phenomena that can be included in a MN model (convection, conduction, jets among others) cannot be included in the FM model. That is why a separate type is considered here for both models.

c. BB – Blackbox

Artificial neural network methods are statistical learning models that operate like a black box validated with a database (experiments or complex models). Outputs are evaluated with the inputs by means of hidden functions. This method has already been applied in the case of a TES [9]. These models are fast but cannot be used for extrapolation outside the calibration range. Sciacovelli ([10]) used a proper generalized decomposition which consists in an enrichment of formula with a priori unknown functions and parameters. The model has been validated for different geometries based on CFD models. This approach allows to use BB with different geometries which is interesting. But, still, it cannot be used with other parameters (inlet and outlet position, internal heat exchanger, thermal insulation variation...), needs to run long CFD simulation several times and is very dependent of the database.

d. MB - Moving Boundary

In this model, an ideal thermocline (negligible thickness) is dividing the storage into two zones with fixed temperatures. The position of the thermocline (which determines the volume of each zone) is given by the energy balance including ambient losses, heat input and output. This model does not take mixing into account and there is no mass transfer between the two zones. This model presents a low CPU time [11]. In 2015, Dickes et al ([5]) developed a two-zone moving boundary with a transition profile of the temperature. The difference with the former model is that the temperature are not fixed anymore but are evaluated with temperatures at former time step and an energy balance in each zone. A dynamic deterministic update of temperature profile (thermocline) is evaluated in function of the time and the flow. It allows to obtain a good accuracy of the stratification compared to a detailed multimode model. This upgraded model is the one which will be referred as MB in the next part of the paper.

e. PF - Plug Flow

In this approach, n-variable volume isothermal disks are assumed to move through the tank without any mixing between them [13]. The modeling is quite simple: When a supply volume is inserted into the tank, a new segment with the prescribed inlet temperature is inserted. In the most common approach, the variable inlet is used (it injects the fluid in the tank in the zone where the temperature level presents the closest temperature to keep a monotonically increasing temperature with the height). If the temperature of the supply volume is close to an already existing segment (typically < 0.5 K), then the supply volume is mixed with the already existing segment. Because the tank presents a finite volume, a volume equivalent to the inlet volume is shifted out of the tank. This model is fast to be computed compared to the multimode (MN) model particularly in the case of high stratification (because of lower

number of nodes required [13]). The PF with variable inlet is interesting because it gives the upper limit of deliverable thermal energy (perfect stratification). This is almost the case practically when low mixing occurs.

f. MN – Multi-Node (or layer)

Other authors develop the multi-node model (one-dimensional finite-volume method). These models consider the following assumptions: uniform horizontal temperature in the horizontal layers and the flow inside the tank is one dimensional [13]. The model applies the conservation of energy for each zone (Eq. 2) taking into account the thermal inertia of the fluid, the enthalpy flow input (\dot{H}_{in}), the enthalpy flow output (\dot{H}_{out}), the conductive losses (\dot{Q}_{cond}) including, or not, other effects such as induced buoyancy flows, jet mixing and plume entrainment and often ambient losses (\dot{Q}_{amb}) eventually including quilting losses.

$$m_i c_i \frac{dT_i}{dt} = \dot{Q}_{cond,i} + \dot{H}_{in,i} - \dot{H}_{out,i} + \dot{Q}_{amb,i} \quad (2)$$

Furthermore, these models often require a relatively high number of cells compared to the former approaches leading to a higher computational time. The high number of cells allows avoiding artificial diffusion (i.e. the smoothing effect due to the successive ideal-mixing of the fluid in each cell [13]. Franke [14] a variable thickness multimode model is developed and allows to use only 6 nodes instead of 15 for a constant thickness multimode model. Various number of MN models predict the temperature profile based on a few semi-empirical fitting parameters.

g. ZN - Zonal

The zonal model developed by Blandin [15] is basically a 3D finite-volume method with a large mesh (division in crown and sectors) where mass and energy balance are verified. The simplification induced by the large mesh and no momentum conservation (compared to CFD models) are compensated by the introduction of laws taking into account plume entrainment, boundary layer flow, jet and quilting. This model is an intermediary between CFD models and MN models in terms of physical phenomena taken into account and CPU time (roughly seven times slower than MN model).

h. CFD - Computational Fluid Dynamics

Modelling tanks with Computational Fluid Dynamics is the most accurate way to model the flow field in the tank. Finite Element Method (FEM) or Finite

Volume Method (FVM) can be applied but the most widespread solution in the case of water tank is the FVM because of its lower computationally expensive nature. In each volume of the mesh, Navier-Stokes equations are applied with mass, momentum and energy conservation laws. Two dimensional CFD models are suited for axisymmetric (or quasi-axisymmetric) tank configurations [16]. If not, three dimensional CFD models have to be used but can lead to much longer simulation time. These models are well suited for design optimization reducing costs that would otherwise be associated to perform experiments. Also, it allows to get useful correlation of local phenomena that can be implemented in faster models [4].

4. Comparison and selection of the optimal model

Table 1 compares the different modeling approaches in terms of the description of physical phenomena, CPU time and the need to have a database to fit parameters (not determinist). The physical phenomena are briefly described in chapter 2. The 8 modeling types considered in this study are: Analytical (AN), Fully Mixed (FM), Blackbox (BB), Moving boundary (MB), Plug Flow (PF), Multi-node (MN), Zonal (ZN) and computational fluid dynamics (CFD).

Table 1. Comparison between the modeling approaches. + is good, - is bad and o is intermediate. * means that it can be integrated in the model but not systematically.

Criterion		A N	F M	B B	M B	P F	M N	Z N	CF D
Physical phenomena	Ambient losses	-	*	-	*	*	+	+	+
	Conduction (water + wall)	-	-	-	*	-	+	+	+
	Mixing due to T° inversion	-	-	-	+	*	*	+	+
	Quilting	-	-	-	*	*	*	+	+
	Parietal induced flow	-	-	-	*	-	*	+	+
	Jets mixing	-	-	-	-	-	*	+	+
	Exchanger/resistor	-	-	-	*	*	+	+	+
	Navier-stokes + obstacles	-	-	-	-	-	-	-	+
CPU time		+	+	+	+	+	O	-	-
Determinist		+	+	-	+	+	+	+	+

Several papers compare results from different modeling approaches [15,17-20]. It should be noted however that conclusions drawn are case dependent and should be taken with care. Also, a given type of model does not give satisfaction in every application. A tree of decision is proposed to select the optimal storage model depending on the main criteria encountered:

application, accuracy, computational time and availability of a database (Fig. 3). AN models are not considered here because of their very narrow range of application.

Here is the way to use the tree of selection: First, if the purpose is to perform an optimal design, CFD models should be chosen because of their high capabilities to model complex flow field inside the tank with a wide range of configuration. When performing simulations of a tank, if experimental data is available, two types are possible, either AN or MN with fitting parameters. Because of their non-extrapolability, AN models would require experimentation on the whole range of inputs which is often long and costly. MN models should therefore be preferred thanks to the semi-empirical modeling assumptions. If no experimental data is available, which is often the case, a model giving the highest accuracy with acceptable CPU time should be chosen. A complexity trade-off must indeed be found for each application. The FM model should not be used because of its very poor accuracy except in the case where stratification is negligible (high flow or small storage) and in the case where a lower bound of performance is required. The MB model with temperature profile is very interesting in terms of accuracy and CPU time but needs further developments to account for internal exchanger(s) and ambient losses relevant in a wider range of applications.

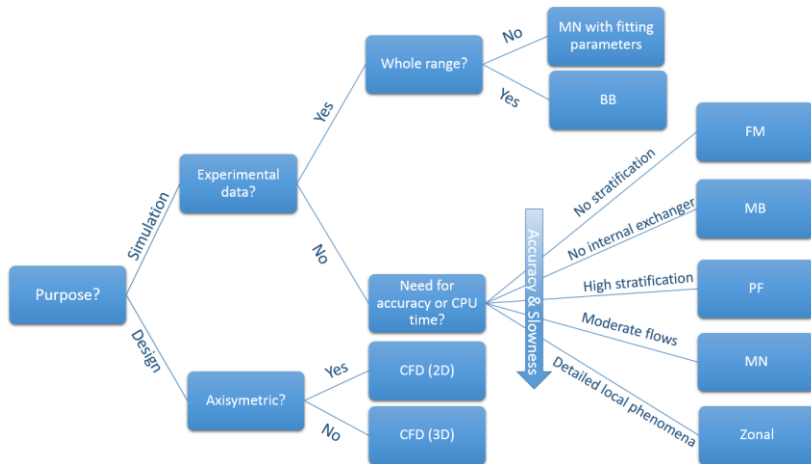


Figure 3: Tree of selection to select the optimal storage modeling approach

The PF model is fast and accurate in the case of high stratification (low flow, low thermal power, large tank, efficient stratification manifold and/or diffuser) and in the case where an upper bound of performance is necessary. The PF model is fast and accurate in the case of high stratification (low flow, low

thermal power, large tank, efficient stratification manifold and/or diffuser) and in the case where an upper bound of performance is necessary. The MN model is the most classical choice for annual simulation because of its decent accuracy but is too slow for optimal control (e.g. Demand Side Management). Finally, the zonal model is the most accurate model that can be used for simulation purposes. But, it requires seven times more CPU time than MN models [14], which could be a rejection criterion for a lot of applications.

5. Conclusion

First, an overview of the different phenomena occurring in hot water tank is performed. Secondly, this paper tries to determine a classification among existing simulation models through the discussion of their hypothesis and limitations. Finally, a selection tree is proposed to the analyst/designer select the optimal model depending on the given application, accuracy, computational time and availability of a database of results.

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